

Lifetime measurement and calibration from pressure-sensitive paint luminescence images

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A dual-image lifetime technique for acquiring surface pressure measurements from pressure-sensitive paint image data has been developed. This technique eliminates the need to acquire a “wind-off” reference image as required by the traditional radiometric technique, which is known to corrupt results. Here a luminescence lifetime-versus-pressure calibration experiment was conducted. Uncertainty was nominally less than $\pm 4\%$ and decreased as signal level increased. The nominal sensitivity was less than ± 5 Torr at 100 Torr, less than ± 50 Torr at 700 Torr, and improved with signal level. © 2003 American Institute of Physics. [DOI: 10.1063/1.1527201]

Pressure-sensitive paint (PSP) surface pressure measurements consist of either a radiometric or lifetime measurement of surface luminescence emission in response to excitation. Image acquisition is followed by Stern–Volmer pressure calibration of the measured surface distribution.^{1–3} Radiometric measurements require ratioing time-integrated images to a “wind-off” reference image. The radiometric procedure is error prone due to variations in object geometry, excitation irradiance, and temperature over the course of an experiment.^{2,4,5} Direct lifetime measurements eliminate these contributions to error because the entire measurement is made after a single excitation pulse. In this note we describe the PSP lifetime technique,³ and report our adaptation of this technique to a lifetime Stern–Volmer calibration experiment. A significantly more detailed report of these experiments is presented by Drouillard.⁶

The excited-state lifetime of PSP following an excitation pulse is selectively reduced by oxygen quenching, thus higher air pressure reduces the lifetime (in microseconds) of PSP emission. The lifetime form of the Stern–Volmer function is

$$\frac{\tau_A}{\tau} = 1 + kP, \quad (1)$$

where τ_A is the single-exponential decay time constant of the luminescence in the absence of oxygen, τ is the single-exponential time constant of the luminescence decay in the presence of oxygen at a partial pressure $[O_2]$ (kPa or Torr), P is the total air pressure, and k is a modified Stern–Volmer coefficient that relates $[O_2]$ to P .³ The actual luminescence

decay of PSP is more accurately modeled by the sum of several exponential terms, but it has been shown that a single decay time constant that most closely fits the luminescence decay can be adequately related to pressure.¹ Equation (1) assumes a linear relationship between pressure P and τ_A/τ ; physical nonidealities result in nonlinear effects that are more accurately modeled by adding higher-order terms. The lifetime pressure calibration function used here, therefore, is⁷

$$P = a + b \frac{\tau_A}{\tau} + c \left(\frac{\tau_A}{\tau} \right)^2. \quad (2)$$

In this work, lifetimes were measured by acquiring two sequential images of luminescence emission following an excitation pulse. We used a dual-image interline-transfer charge coupled device (CCD) camera that produces 1300×1030 pixel, 12-bit-grayscale images (MicroMax-5 MHz from Roper Scientific). In this evaluation, pixel values were spatially averaged and designated m_1 for the first image and m_2 for the second image. Each measurement value represents luminescence emission integrated over the duration of the exposure; the exposure intervals were $2 \mu s \leq t \leq 32 \mu s$ for the first image and $32 \mu s \leq t \leq 8.03$ ms for the second image (relative to an excitation pulse at $t=0$). Analytically, as described by Goss *et al.*,³ m_1 and m_2 were calculated by integrating a decaying exponential function $I_0 \exp(-t/\tau)$, giving

$$m_1 = I_0 \tau (e^{-t_0/\tau} - e^{-t_1/\tau}) \quad (3)$$

and

$$m_2 = I_0 \tau e^{-t_1/\tau}, \quad (4)$$

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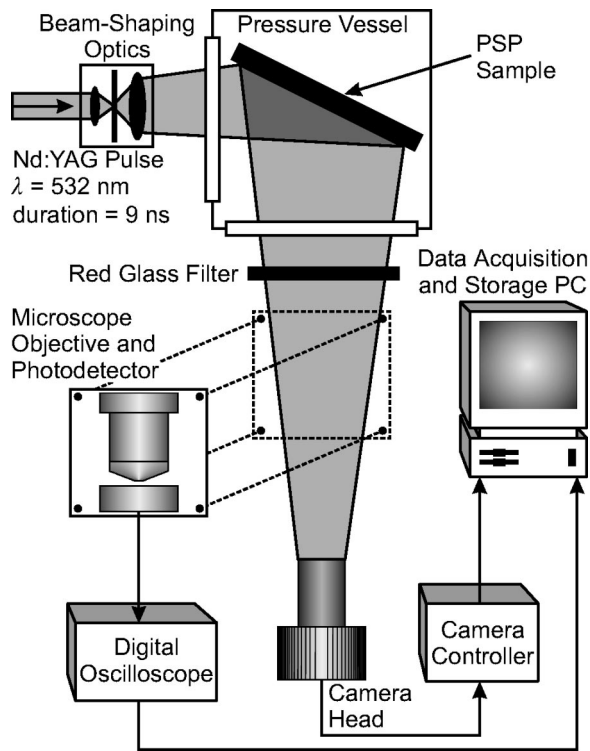


FIG. 1. Laboratory setup for lifetime-pressure calibration experiments.

where (t_0, t_1) is the interval of the first exposure, $(t_1, t \gg \tau)$ is the interval of the second exposure, I_0 is the irradiance at $t=0$, and τ is the luminescence lifetime. An expression for lifetime calculated from $r_m = m_1/m_2$ is

$$\tau = \frac{t_1 - t_0}{\ln(1 + r_m)}. \quad (5)$$

The laboratory setup shown in Fig. 1 was used to acquire lifetime measurements of a PSP sample at static pressures between 100 and 700 Torr. The PSP used was a fluorinated platinum porphyrin compound [UNI-001 Pt(TfPP)-Unicoat-Based PSP from Innovative Scientific Solutions, Inc.]. Lifetime-versus-pressure data were fit to Eq. (2) by a nonlinear regression algorithm. The resulting calibration function was

$$P = 28.82 - 108.1 \frac{\tau_A}{\tau} + 180.3 \left(\frac{\tau_A}{\tau} \right)^2 [\text{Torr}], \quad (6)$$

where $\tau_A = 51.37 \mu\text{s}$. The calibration is plotted in Fig. 2. Lifetime measurements were repeated with a photodetector in place of the camera. Decaying luminescence irradiance was sampled at static pressures between 100 and 400 Torr. Calibration results from photodetector data were within 3% of camera results over this interval.

When a cooled scientific-grade camera is used, uncertainty is dominated by shot noise (Poisson uncertainty associated with photoelectron counting) and scene noise (measurement discrepancies due to variations in pixel response),⁸ since the present technique eliminates geometric distortion, ratioing eliminates scene noise.² The present uncertainty derivation was based on the work of Liu *et al.*⁹ and Goss *et al.*,³ and employed standard error propagation

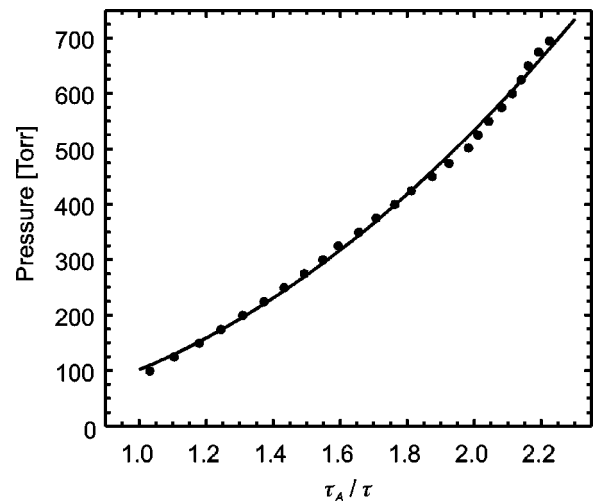


FIG. 2. Stern-Volmer data obtained by camera measurements and fitted calibration curve.

techniques.¹⁰ Shot noise was propagated through the luminescence lifetime calculation, then through the quadratic Stern-Volmer calibration, concluding with the pressure uncertainty plot in Fig. 3. The pressure uncertainty plot shows that for nominal signal levels, the uncertainty in pressure is $\sim 2\% - 5\%$.

The uncertainty plotted in Fig. 3 was calculated as follows. A background-subtracted CCD pixel value m is proportional to the number of photoelectrons accumulated in an electron well during an exposure n_{pe} . The constant of proportionality is $G_{CCD} = (\text{CCD count range})/(\text{electron well depth})$. The camera used in these experiments has a well depth of 18×10^3 electrons and a range of 3959 counts after background subtraction. Shot noise is $\Delta n_{pe} = \sqrt{n_{pe}}$, and the uncertainty in m due to shot noise is $\Delta m = \sqrt{G_{CCD} m}$. Propagation of Δm_1 and Δm_2 through Eq. (5) gives

$$\frac{\Delta \tau}{\tau} = \sqrt{\frac{G_{CCD}}{m_1} + \frac{G_{CCD}}{m_2}} \frac{m_1}{(m_1 + m_2) \ln(1 + m_1/m_2)}. \quad (7)$$

Equation (7) was used to calculate $\Delta \tau/\tau$, this was propagated through Eq. (6) to give

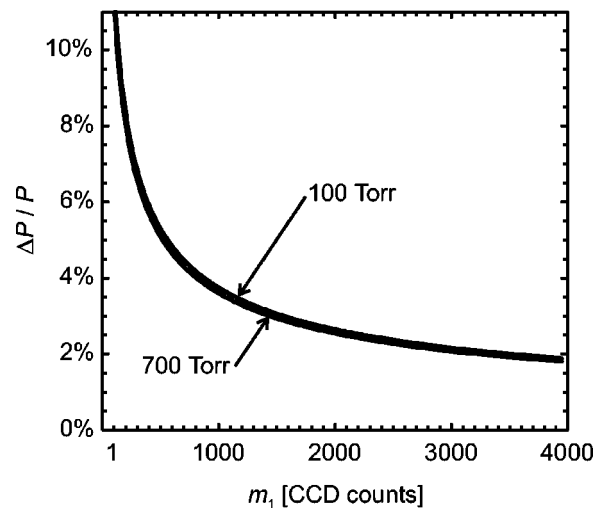


FIG. 3. Relative pressure uncertainty vs signal level at 100 and 700 Torr.

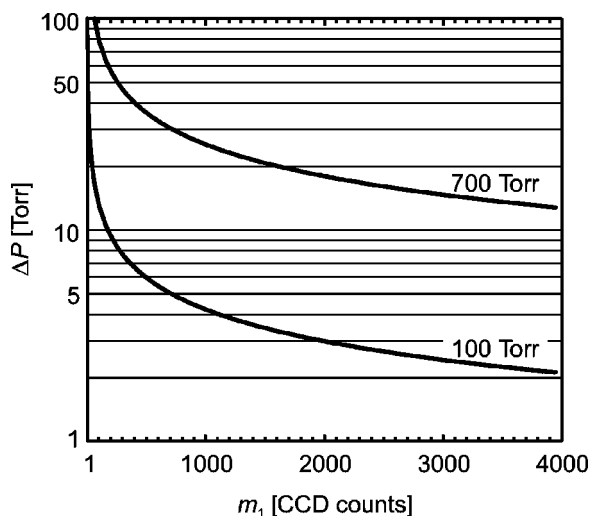


FIG. 4. Pressure sensitivity vs signal level at 100 and 700 Torr.

$$\frac{\Delta P}{P} = \frac{b \frac{\tau_A}{\tau} + 2c \left(\frac{\tau_A}{\tau} \right)^2}{a + b \frac{\tau_A}{\tau} + c \left(\frac{\tau_A}{\tau} \right)^2} \left(\frac{\Delta \tau}{\tau} \right). \quad (8)$$

It was observed that r_m varies with pressure such that $m_2 = 1.192 m_1$ at 100 Torr and $m_2 = 0.365 m_1$ at 700 Torr. These substitutions were made in Eq. (8) so that pressure uncertainty could be plotted as a function of m_1 at 100 and 700 Torr.

Sensitivity, the smallest detectable change in pressure, was based on similar calculations by Liu *et al.*,⁹ adapted to the lifetime technique. Pressure sensitivity was

$$\Delta P = \frac{\partial P}{\partial r_m} \Delta r_m, \quad (9)$$

where Δr_m was calculated by propagating uncertainties in m_1 and m_2 through the ratio expression, giving

$$\Delta r_m = \frac{m_1}{m_2} \sqrt{\frac{G_{\text{CCD}}}{m_1} + \frac{G_{\text{CCD}}}{m_2}}. \quad (10)$$

Again substituting $m_2 = 1.192 m_1$ at 100 Torr and $m_2 = 0.365 m_1$ at 700 Torr, sensitivity was plotted versus m_1 in Fig. 4. This result shows that pressure sensitivity improves with the signal level, as one would expect.

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¹J. N. Demas, B. A. DeGraff, and P. B. Coleman, *Anal. Chem.* **71**, 793A (1999).

²R. C. Crites, VKI Meas. Technol., 1993.

³L. P. Goss, D. D. Trump, B. Sarka, L. N. Lydick, and W. M. Baker, "Multi-dimensional time-resolved pressure-sensitive-paint technique: a numerical and experimental comparison," AIAA Paper 2000-0832, 38th Aerospace Sciences Meeting & Exhibit, 2000.

⁴W. Ruyten, *AIAA J.* **38**, 1692 (2000).

⁵K. R. Navarra, M. S. thesis, Virginia Polytechnic Institute and State University, 1997.

⁶T. F. Drouillard II, Ph.D. thesis, Colorado School of Mines, 2002.

⁷L. M. Coyle and M. Gouterman, *Sens. Actuators B* **61**, 92 (1999).

⁸D. R. Mendoza, *ICIASF'97 Record*, 1997, pp. 22–29.

⁹T. Liu, M. Guille, and J. P. Sullivan, *AIAA J.* **39**, 103 (2001).

¹⁰P. R. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 2nd ed. (WCB/McGraw-Hill, Boston, 1992), Sec. 8.6.